

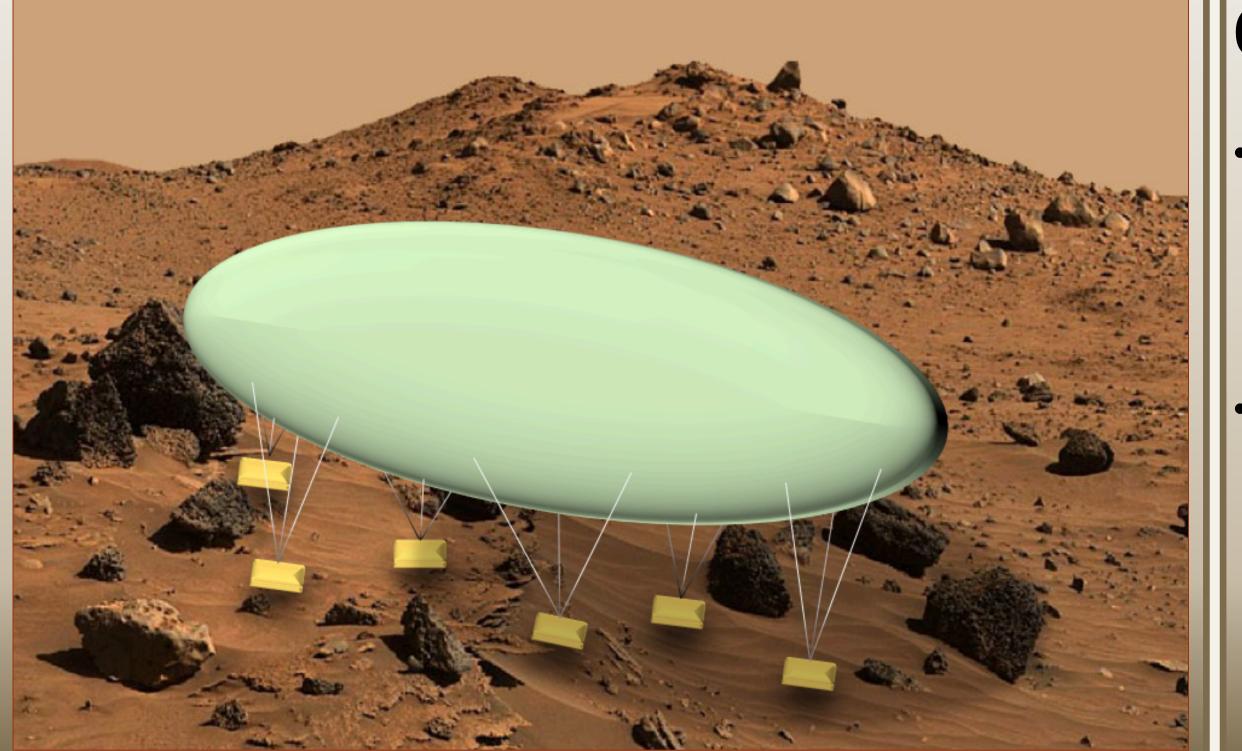
#### **BALLET: BALloon Locomotion for Extreme Terrain**

Hari Nayar, Michael Pauken, Morgan Cable, Michael Hans, Roger Fowler Jet Propulsion Laboratory, California Institute of Technology Program: NASA NIAC Phase I Contact: Hari Nayar, Ph 818 393 2505; Email hdnayar@jpl.caltech.edu

# Jet Propulsion Laboratory California Institute of Technology

#### **Concept Overview**

- BALLET offers a new approach for traverse over extreme terrain on planetary surfaces with atmospheres
- Balloon platform with 6 suspended modules, each containing a science payload that also serves as a foot
- Each foot is suspended by 3 cables that are used to control the placement of the foot on the ground
- Only 1 foot/payload is raised at a time; remaining feet keep the balloon anchored to the surface.
- Feet are moved in sequence to locomote over the surface The platform is highly stable because its center of gravity is at ground level
- Images from cameras on the balloon are used to map and locate foot



#### Objectives

- Evaluate feasibility of a BALLET mission concept for locomotion and science operations on extreme terrain on Mars and Titan
- Determine optimal design parameters for performance using an analytical and physicsbased simulation approach

#### Force & Moment Balance Analysis

- On Mars: A 5-meter balloon with 1-kg feet would have adequate buoyancy for locomotion and withstand drag forces due to winds with nominal speeds of 10-m/s
- On Titan: A 3-meter balloon with a 45-kg RTG power system and 5-kg feet would have adequate buoyancy for locomotion and withstand drag forces due to winds with nominal speeds of 1-m/s

		<u> </u>	
ravitational accel (m/s²)	9.807	3.710	1.352
urface atm density (kg/m³)	1.217	0.020	5.280
elium surface density (kg/m³)	0.178	0.002	0.728
ominal wind speed (m/s)	7.000	10.000	1.000
rag coeff	0.500	0.500	0.500
oot mass (kg)	1.000	1.000	5.000
dded mass on balloon (kg)	0.500	0.100	45.000
eeded balloon buoyancy force (N)	19.614	5.936	70.980
alloon volume (m³)	1.925	88.134	11.534
alloon diameter (m)	1.543	5.521	2.803
alloon x-section area (m²)	1.871	23.943	6.172
ominal wind drag force (N)	27.891	11.972	8.147
ravity anchoring force (N)	44.132	16.695	30.420

Earth Mars Titan

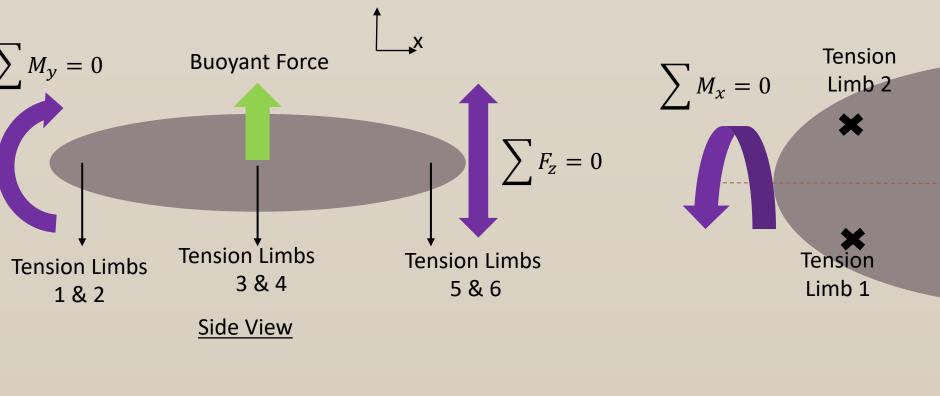
- For detail analysis, each limb is estimated as a single cable hanging in the center of the three connection points
- When lifting one or more feet for locomotion, the tensions are no longer equal. Solving for the tensions is an underdetermined problem.

Equations
$$\sum M_{y} = 0 , \sum M_{x} = 0 , \qquad \sum F_{z} = 0$$

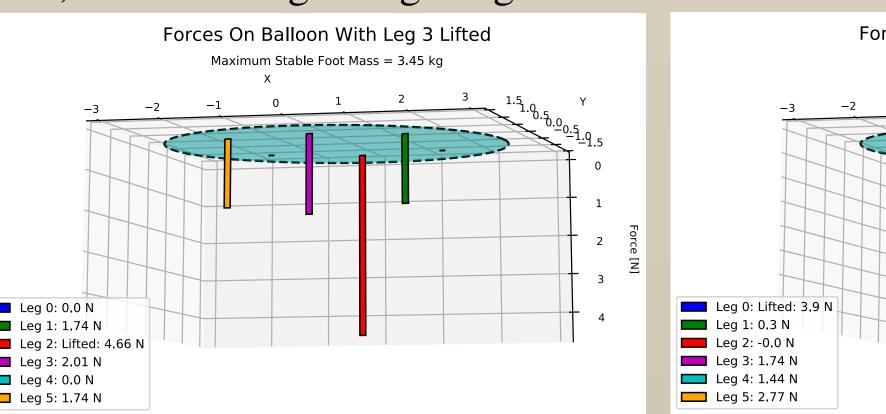
#### Unknowns

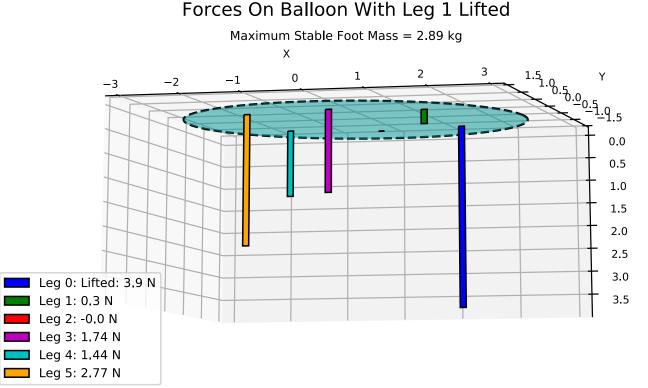
 $T_n \ge 0$  Tension for all limbs n that are not being lifted

- When one or two legs are lifted, there are more unknowns than equations
- The least squares method was used to find the tensions in cables when specific legs are lifted with a known mass attached to the foot
- Optimization was performed to find the maximum foot mass that still resulted in a stable balloon.



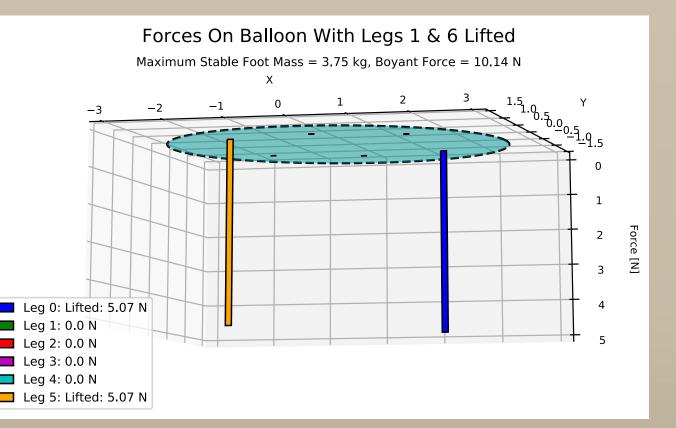


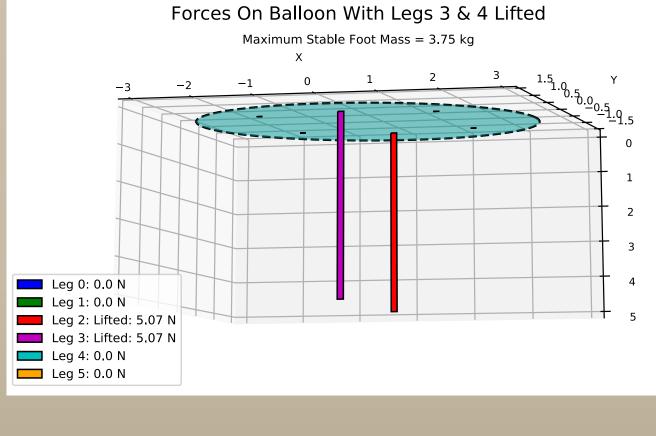




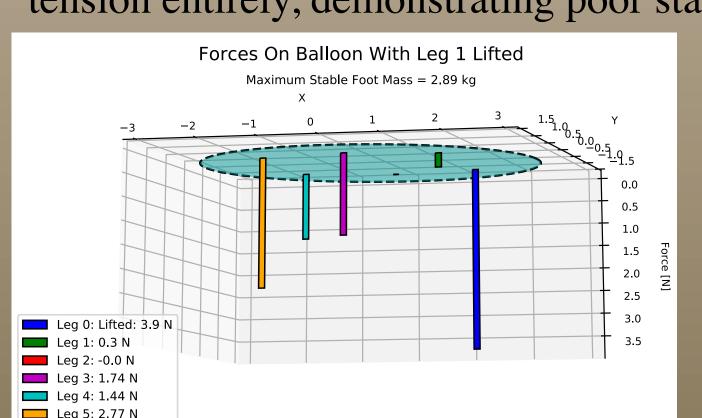
Result: The foot mass for a balloon on Titan that lifts one leg at a time must be greater than 1.25 kg and less than 2.89 kg to remain stable

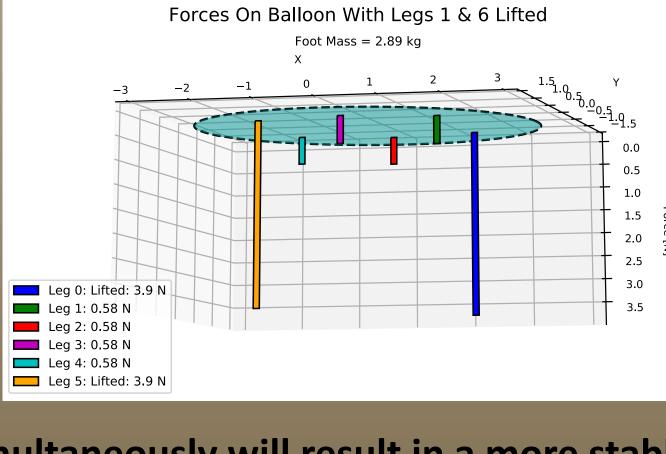
- Next, look at lifting a two legs on the same balloon
- Result: The foot mass for a balloon on Titan that lifts two legs at a time must be greater than 1.25 kg and less than 3.75 kg to remain stable
- Lifting opposite legs simultaneously negates the moment that would otherwise have to be counteracted by other cables. This allows for the feet to have greater mass than when lifting one leg at a time, while maintaining high stability





- Using a mass of 2.89 kg, it can be clearly seen why lifting two feet is more stable than lifting one:
- Lifting two legs, at the stable foot mass found for a single lifted leg, results in all cables maintaining tension. When a single leg is lifted, one cable loses tension entirely, demonstrating poor stability





- placement and for navigation

Enables in-situ science operations at scientifically exciting

Use of a balloon for buoyancy and as a platform for

• Limbs composed of cables in tension with significantly

• Partitioning the payload into six modular elements and

less mass than legs composed of links in compression

lifting of only one at a time to significantly reduce the

• Placement of the payload in the feet keeping the center of

Achieves its benefits through several innovations:

**Novelty and Innovation** 

but previously inaccessible locations

needed buoyancy and balloon size

#### Technical Approach

- Develop designs of mission concepts to Mars and Titan to perform contact science on rugged terrain
- Identify mission requirements, baseline instruments and housekeeping services
- Select materials, balloon deployment mechanism, inflation system, ground shield, and operational procedures consistent with mission and environmental constraints based on prior research on atmospheric balloon missions to Titan and Mars.
- Model 3-D buoyancy and gravitational forces in the environmental conditions on Titan and Mars, wind conditions, aerodynamics and drag forces
- Study variations in environmental temperature and its impact on buoyancy
- Study drag forces on the balloon due to wind and stability of this system under varying wind conditions
- Determine performance on steep terrain
- Implement path planning, foot placement and cable control algorithms on realistic terrain
- Improve performance through the optimization of design parameters

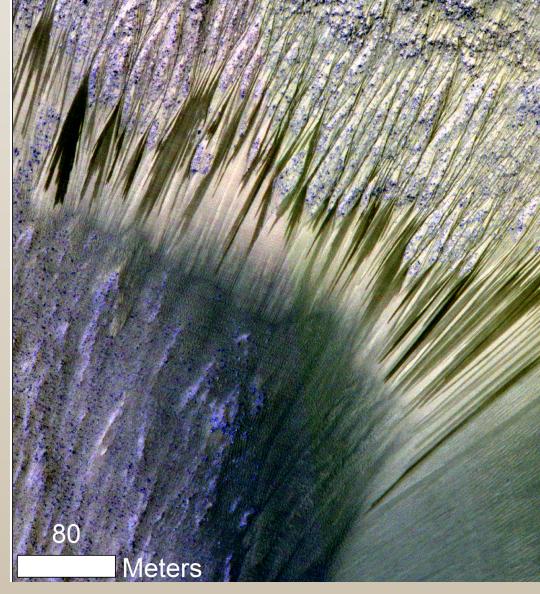
#### Science Objectives and Payload

gravity very low and the platform highly stable

 Mars Recurring Slope Lineae (RSL)

locomotion

- Seasonal events comprised of either liquid brine flows or dry granular avalanches
- Targets of investigations for habitability and/or astrobiology
- Requires access to terrain with slopes of 27-40 degrees (the steepest slope attempted by a rover on Mars was 32 degrees)

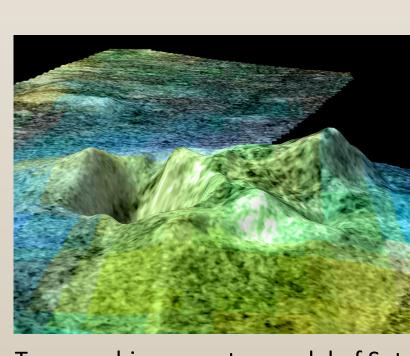


RSL observed by HiRISE emanating from Palikir

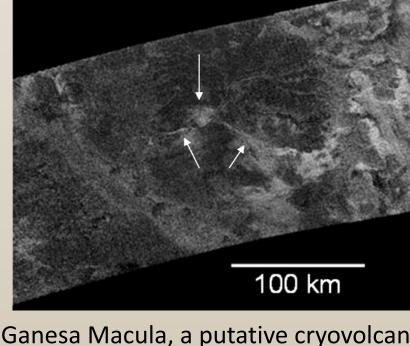
	crater during southern summer. Credit: NASA/JF			
Science Objective	Payload Element [Example]	Mass (kg)	<sup>a</sup> Entire REMS met package (including sensors for wind,	
Determine if RSLs are formed by iquid water or dry grains	Relative humidity sensor [REMS-H on MSL]	<<1 <sup>a</sup>	was 1.243 kg.  b Includes components such as	
	pH/eH/conductivity [TECP on Phoenix robotic arm]	<1	optical and atomic force microscopes which would not	
	Ion selective electrodes [WCL on Phoenix MECA]	<8.5 <sup>b</sup>	required for BALLET.  c Proposed but ultimately	
Search for evidence of habitability/life	Organic microfluidics detector [Urey on ExoMars <sup>c</sup> ]	4.4	descoped. Mass estimate is from 2008, probably out-of-date for any new prototype.	

#### Titan Cryovolcanic Flows

- Eruption of volatiles (water, ammonia, methane) from Titan subsurface
- Some evidence, but not yet confirmed



Topographic computer model of Sotra Patera, a putative cryovolcano on Titan. Credit: NASA/JPL-

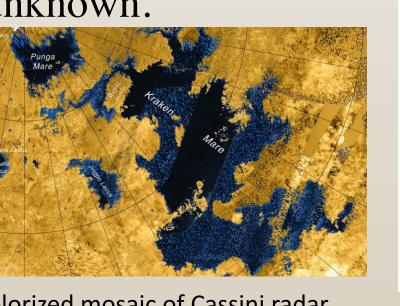


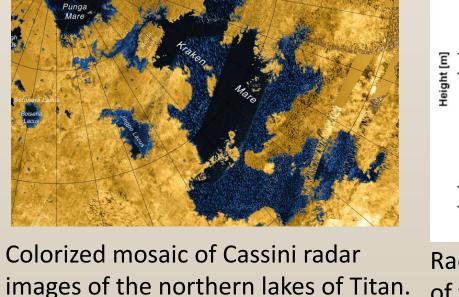
channe	els (Lopes et al. 2007).  Payload Element	Mass
	Payload Element [Example]	Mass

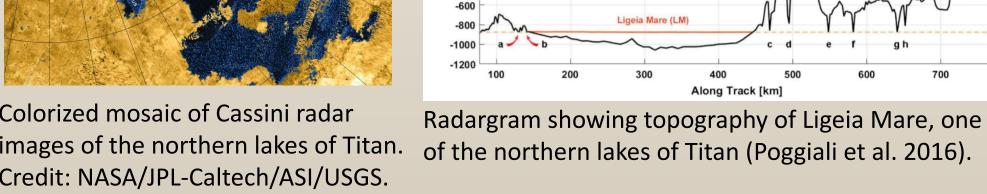
altech/USGS/Univ. of Arizona. channels (Lopes et al. 2007).			
Science Objective	Payload Element [Example]	Mass (kg)	(
etermine whether organics have been altered y liquid water (i.e., search for amino acids and ther products of hydrolysis or oxidation).	Laser desorption ionization mass	1.6	ı,
etermine the age of the cryovolcanic flow via otopic ratios ( $^{13}$ C/ $^{12}$ C, D/H).	spectrometer [MOMA on ExoMars]		
y composition of the cryovolcanic flow, etermine: (1) if it is sourced from the liquid rater ocean and, if so, (2) the composition of ne ocean.	Raman spectrometer [SHERLOC on Mars 2020]	1.6	
ssess whether cryovolcanic flow composition nd morphology varies over the surface of the ow.	Context camera [Mastcam-34 on MSL]	0.8	
	NIR imaging spectrometer [UCIS prototype]	1.5	* W

• Titan Lake Shorelines

 Confirmed presence of liquid hydrocarbon lakes on Titan, but the composition and their shorelines is still unknown.







Cledit. NASA/JF L-Caltecti/ASI/0303.				
Science Objective	Payload Element [Example]	Mass (kg)		
Determine lake composition (both hydrocarbons and dissolve components)	Immersion probes – UV/vis for dissolved aromatics, NIR for methane/ethane/propane ratio [FOCALS prototype]	<1		
Determine composition of the shoreline	Raman spectrometer [SHERLOC on Mars 2020]	1.6		
	Laser Desorption Ionization MS [MOMA on ExoMars]	1.6		
Identify lake dynamics (wave activity, bubbles due to exsolvation, etc.)	Context camera [MAHLI on MSL]	<0.5		
	Bubble size/distribution probe [EnviroCam prototype]	<<1		
	Meteorology package [SSP of Huygens probe]	4.2*		
* The Surface Science Package includes sensors for permittivity and acoustic properties which				

ill not be required. This instrument suite could also be split into multiple packages to meet

foot positions

Top View P3

 $y_r^2 = x_d^2 + (y_r - y_d)^2$ 

 $y_r = (x_d^2 + y_d^2)/(2y_d)$ 

 $\theta_d = 2 \operatorname{atan2}(y_d, x_d)$ 

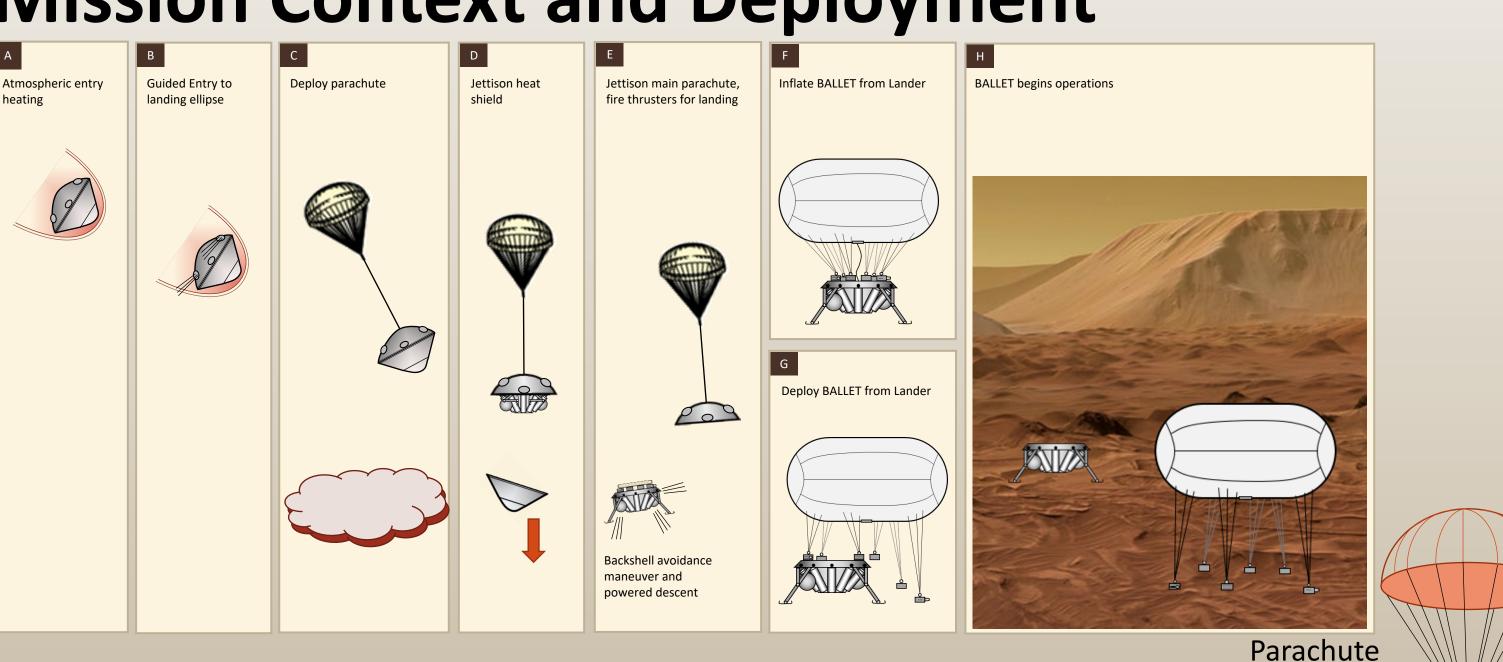
 $y + \theta_d$  arc angle

 $= x_d^2 + y_r^2 - 2 y_r y_d + y_d^2$ 

d balloon path length

Destination

### Mission Context and Deployment



The deployment sequence for BALLET upon entry as shown here.

- Enter atmosphere after separation from carrier vehicle. Guided entry targets the landing ellipse firing thrusters to maneuver.
- Parachute deployed at supersonic speed
- to avoid collision with backshell upon landing. Relative terrain navigation guides lander to safe location. BALLET balloon is inflated from the top of the lander and the payload elements.
- H. BALLET fully deployed and ready to move to science targets.

**National Aeronautics and Space Administration** 

**Jet Propulsion Laboratory** 

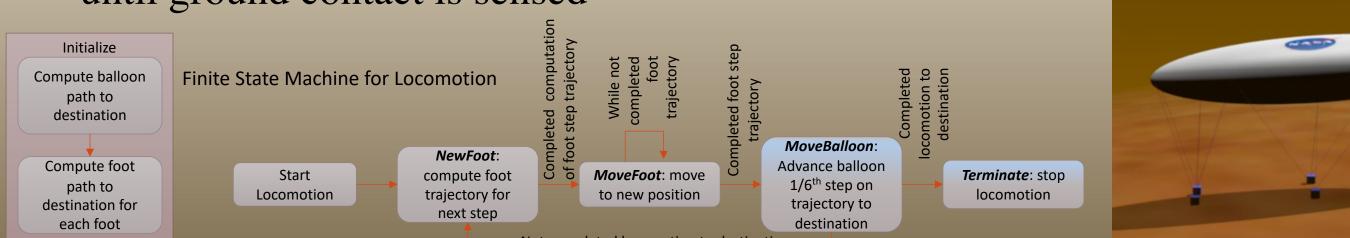
Pasadena, California

California Institute of Technology

Backshell Heat shield separates from the vehicle. Lander separates from parachute and backshell. Lander performs a backshell avoidance maneuver upwind BALLET Inflation system G. The BALLET vehicle moves off the lander. & Lander

- accomplished by traversing along a curved path. For a desired destination, corresponding curved paths for
- the balloon and each foot are computed. Each balloon and feet path is discretized into steps.
- Locomotion occurs by taking a step with one foot, moving the balloon one-sixth of its step, then taking a step with another foot and so on until all the feet have taken a step and the balloon has moved a full-step. This is repeated until the balloon reaches its destination. The state-machine
- the 3 cables attached to each foot as shown on the right:
- foot up
- The foot is then lowered by lengthening all three cables

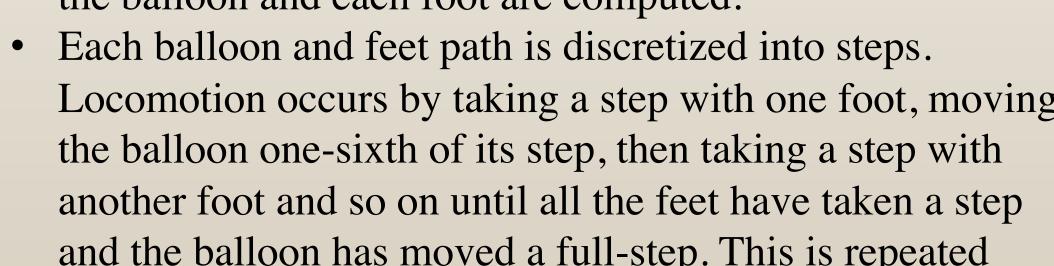
are then shortened further while lengthening the cable

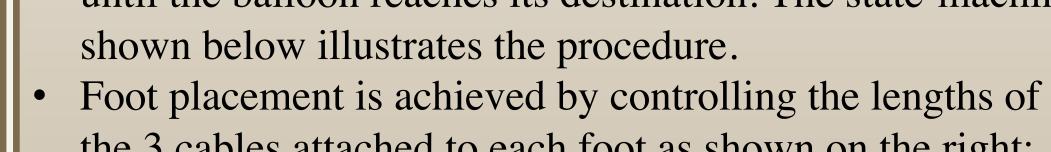


The research described in this poster was carried out at the Jet Propulsion Laboratory of California Institute of Technology under contract from the National Aeronautics and Space Administration. Pre-decisional information, for planning and

### **Mobility and Locomotion**







• To take a step, all three cables are shortened to raise the • The cables attached at points P1 and P3 on the balloon

until ground contact is sensed

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## **Acknowledgement**

attached at P2 to move the foot to P4'

Locomotion lifting two opposite legs simultaneously will result in a more stable balloon, and allow for more science instruments to be carried